

# Variable stars in the field of the old open cluster Melotte 66

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## ABSTRACT

We report the results of photometric monitoring of the Melotte 66 field in *BVI* filters. Ten variables were identified with nine being new discoveries. The sample includes eight eclipsing binaries of which four are W UMa type stars, one star is a candidate blue straggler. All four contact binaries are likely members of the cluster based on their estimated distances. Ten blue stars with  $U - B < -0.3$  were detected inside a  $14.8 \times 22.8$  arcmin<sup>2</sup> field centred on the cluster. Time series photometry for 7 of them showed no evidence for any variability. The brightest object in the sample of blue stars is a promising candidate for a hot subdwarf belonging to the cluster. We show that the anomalously wide main sequence of the cluster, reported in some earlier studies, results from a combination of two effects: variable reddening occurring across the cluster field and the presence of a rich population of binary stars in the cluster itself. The density profile of the cluster field is derived and the total number of member stars with  $16 < V < 21$  or  $2.8 < M_V < 7.8$  is estimated conservatively at about 1100.

**Key words:** binaries: close – open cluster and associations: individual: Melotte 66

## 1 INTRODUCTION

Melotte 66 ( $\alpha = 07^{\text{h}}26^{\text{m}}21.^{\text{s}}9$ ,  $\delta = -47^{\circ}41'19''$ , J2000) belongs to a small sample of old galactic open clusters (Kassis et al. 1997). It is located at a relatively large galactic latitude ( $l = 259^{\circ}6$ ,  $b = -14^{\circ}3$ ). A pioneering study, based on the photographic photometry was conducted by Eggen & Stoy (1962). Subsequent investigations based on photographic and photoelectric photometry (Hawarden 1976; Anthony-Twarog et al. 1979) were followed by several papers published in the last two decades of the 20th century. Kassis et al. (1997) used deep *VI* photometry to derive an age of  $4 \pm 1$  Gyr and distance modulus  $(m - M)_0 = 13.2^{+0.3}_{-0.1}$ . Anthony-Twarog et al. (1994) used *vbyH $\beta$*  data to discuss the possible causes of an atypically wide cluster main sequence which was originally noted by Anthony-Twarog et al. (1979). They excluded differential reddening across the cluster field as a cause of this effect.

The cluster stands out from the sample of the known old open clusters in its exceptionally low metallicity. Twarog

et al. (1995) derived  $[\text{Fe}/\text{H}] = -0.53 \pm 0.08$  based on *UBV* photometry of turnoff stars. Friel & Janes (1993) obtained  $[\text{Fe}/\text{H}] = -0.51 \pm 0.11$  from a spectroscopic analysis of 4 giants while Gratton & Contarini (1994) derived  $[\text{Fe}/\text{H}] = -0.38 \pm 0.15$  from high resolution spectra of two giants.

This paper is a contribution to the systematic search for short period variables in open clusters conducted by our group over the last two decades. One of the goals is to establish a relation between age and a relative frequency of occurrence of contact binaries in stellar clusters. A summary of some of our earlier results can be found in Rucinski (1998). Here we report the results of a survey for variable stars in the field of Melotte 66 and also present deep CCD *UBVI* photometry for the cluster.

## 2 OBSERVATIONS AND REDUCTIONS

The field of Melotte 66 was surveyed for variable stars with the 1-m Swope telescope at Las Campanas Observatory. The observations were collected on a total of 21 nights during 4 observing runs during the period February–March 1992. Two different cameras were used: a  $1024 \times 1024$  Tektronics CCD with a scale of  $0.61$  arcsec pixel<sup>-1</sup> (TEK2 camera with a  $10.4 \times 10.4$  arcmin<sup>2</sup> field) and a  $2048 \times 2048$  Ford Aerospace

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**Table 1.** Summary of Melotte 66 observations

Run	Dates	Nights no	No of exposures			Median seeing in V filter
			B	V	I	
FORD2-1	03-08.02.1992	5	8	59	–	1''5
FORD2-2	20-24.03.1992	3	–	12	44	1''2
TEK2-1	09-16.02.1992	7	–	134	5	1''5
TEK2-2	13-18.03.1992	6	68	66	–	1''5

CCD with a scale  $0.435 \text{ arcsec pixel}^{-1}$  (FORD2 camera with a  $14.8 \times 14.8 \text{ arcmin}^2$  field).

Most of the images were collected with a *V* filter with exposure times ranging from 60 s to 480 s with a median value of 420 s. Exposures were also obtained in the *B* and *I* bands. A summary log of the observations is listed in Table 1. An additional set of *UBVI* observations to calibrate the photometry and to construct a color-magnitude diagram (CMD) for the cluster field was obtained on the nights of 1999 November 17–20 (UT) using the  $2048 \times 3150$  SITE3 camera. With a scale of  $0.435 \text{ arcsec pixel}^{-1}$  this camera provides a field of view of  $14.8 \times 22.8 \text{ arcmin}^2$ . Several exposures of different length were obtained in each of the four filters. All images were corrected for the known non-linearity of the SITE3 camera using the procedure described in Hamuy et al. (2006).

Preliminary processing of the CCD frames was done with standard routines in the IRAF-CCDPROC<sup>1</sup> package. Profile photometry was extracted using the DAOPHOT/ALLSTAR package (Stetson 1987). For each camera/filter combination a "master" frame was selected. This was used to create a reference list of objects to be measured in the fixed-position mode on the remaining frames. Instrumental magnitudes were transformed to the system defined by the master frame. The resulting data bases were searched for variable objects using codes using the analysis of variance (AoV) statistic (Schwarzenberg-Czerny 1996) and the AOVTRANS algorithm (Schwarzenberg-Czerny & Beaulieu 2006). AoV periodograms were calculated for periods spanning the range from 0.05 days to 20 days. After the rejection of some spurious detections we ended up with a list of 10 certain variable stars. Nine of these are new discoveries while one is an eclipsing binary V345 Pup reported by Kaluzny and Shara (1988). Equatorial coordinates of the variables were determined using 1651 stars from the USNO A-2 catalog (Monet et al. 1998) which were identified on the *V*-band image obtained with the SITE3 camera. These coordinates are listed in Table 2 along with the coordinates of a UV bright star labelled C1 (see Sec. 3.1) The last column of Table 2 gives the angular distance from the cluster centre as determined from our data ( $RA(2000) = 07^h 26^m 21.^s 9$  and  $DEC(2000) = -47^\circ 41' 19''$ ). In Fig. 1 we present finding charts for the stars listed in Table 2.

**Table 2.** Equatorial coordinates of variables and a UV bright star in the field of Melotte 66

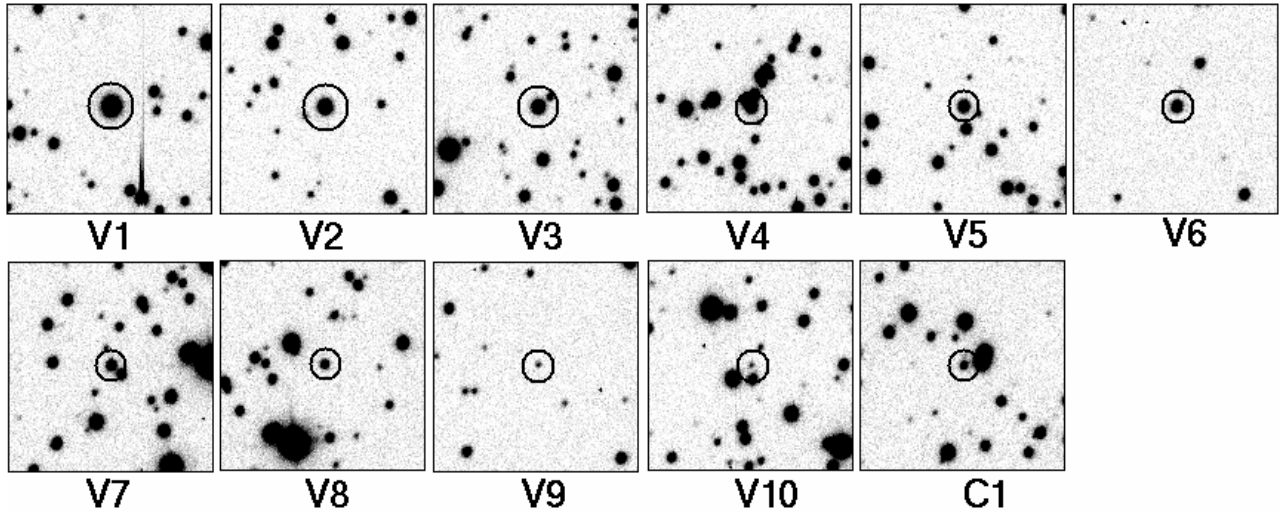
ID	$\alpha_{2000}$ [deg]	$\delta_{2000}$ [deg]	r[arcmin]
V1	111.59873	−47.70060	0.78
V2	111.53339	−47.62291	4.58
V3	111.61123	−47.67409	1.18
V4	111.57849	−47.69664	0.71
V5	111.56815	−47.64329	2.87
V6	111.72366	−47.76692	7.12
V7	111.56230	−47.72299	2.38
V8	111.54562	−47.71756	2.54
V9	111.71073	−47.75736	6.35
V10	111.63718	−47.68840	1.85
C1	111.57537	−47.74433	3.31

## 2.1 Photometric calibration

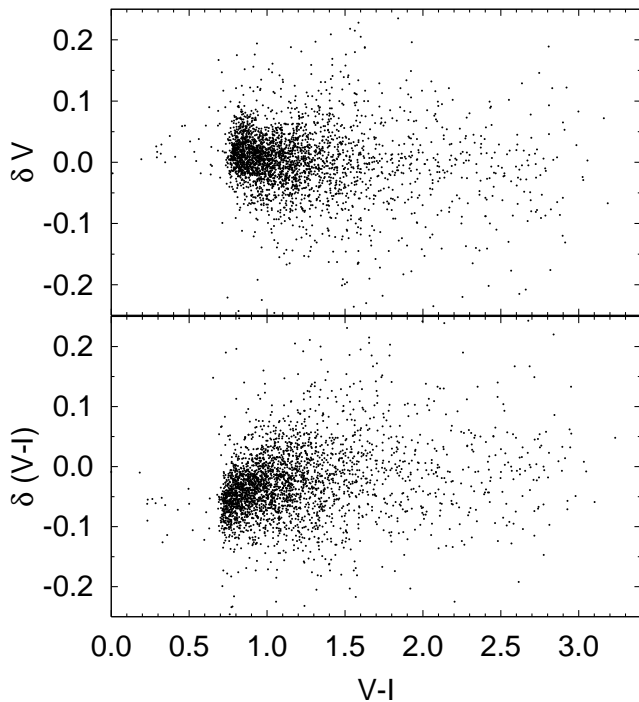
We have used the data collected on the night of 1999 November 18 to calibrate our photometry. Observations of the cluster field were bracketed by observations of three Landolt fields containing a total of 28 standard stars with *BVI* magnitudes (Landolt 1992; Stetson 2000) and 19 stars with *U* magnitudes (Landolt 1992). The T Phe field was observed twice while each of the RU 149 and RU 152 fields was observed once. Standards were observed at air-masses spanning the range 1.12–1.24 while Melotte 66 was observed at an air-mass of about 1.1. Average extinction coefficients for Las Campanas were assumed in determining the linear transformations between the instrumental and the standard system. The total uncertainties of the zero points of our photometry are about 0.02 mag for *BVI* filters and about 0.1 mag for the *U* filter. These uncertainties include errors in the aperture corrections derived for the frames of Melotte 66. The relatively poor quality of the *U*-band transformation can be explained by large differences in the UV spectral responses of the SITE3 CCD camera and the RCA 1P21 photomultiplier defining the *UBV* system (Johnson 1963). The median values of the formal internal errors of our photometry for the cluster range from  $\sigma_V = 0.010$  and  $\sigma_{V-I} = 0.021$  at  $V = 15.5$  to  $\sigma_V = 0.018$  and  $\sigma_{V-I} = 0.027$  at  $V = 19.5$ .

We compare our *VI* photometry with the data taken from Kassis et al. (1997) in Fig. 2. The mean difference (in the sense of "our" measurements minus "theirs") is  $-0.005 \pm 0.001$  and  $-0.023 \pm 0.001$  for *V* and *V − I*, respectively. There is no clear color dependence of the residuals for the *V* magnitudes. There are some systematic trends for the *V − I* residuals.

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.



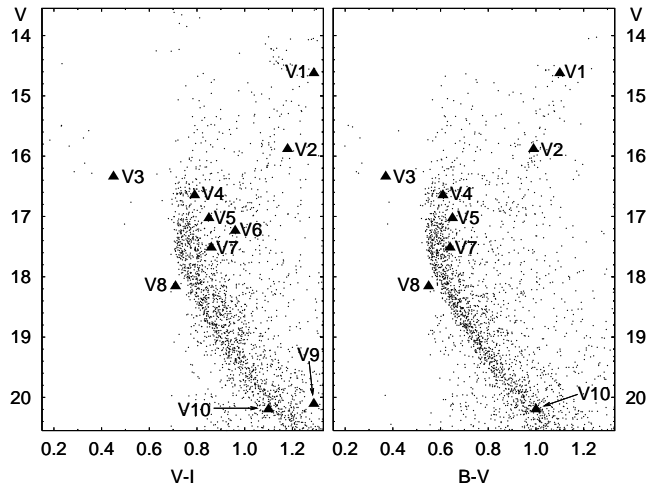
**Figure 1.** Finding charts for variables V1–V10 and for the UV bright star C1. Each chart is 1 arcmin on a side, with east to the left and north up.



**Figure 2.** Residuals of  $V$  and  $V - I$  for this work and Kassis et al. (1997) as a function of  $V - I$ .

### 3 RESULTS FOR VARIABLES

Table 3 lists some basic characteristics of the light curves of variables V1–V10. For each star we list  $V$  magnitude and colors measured at maximum light. The full range of observed magnitudes in the  $V$  band is listed as  $\Delta V$ . The location of the variables on the cluster  $V/B - V$  and  $V/V - I$  diagrams is shown in Fig. 3 while their light curves are presented in Figs. 4–6. Stars V3–10 show periodic variability and can be classified as eclipsing binaries (EC). Moreover, stars V4, V6, V8 and V9 are likely contact binaries (EW) based on their



**Figure 3.** Color-magnitude diagrams of Melotte 66 field with marked positions of variables.

periods, colors and light curves. Variables V1 and V2 are located on or near the cluster subgiant branch while eclipsing binary V3 is a candidate blue straggler. Three other non-contact binaries are located on or slightly above the cluster main sequence. Unfortunately, none of these seem to be a good candidate for spectroscopic follow-up aimed at a determination of cluster distance and age. V5 shows shallow eclipses while V10 is too faint for high resolution spectroscopy. The light curve of V7 is well defined and its shape indicates that the system is a likely semi-detached algol.

All variables are located inside the cluster radius which we estimate at  $9.2$  in Sec. 4. An examination of the angular distances listed in Table 2 shows that most of the variables are in the central part of Melotte 66. There is radial velocity information available for only one of the variables. Collier & Reid (1987) list  $V_r = 75 \pm 7 \text{ km s}^{-1}$  for V2=#1210 based on a single observation. The mean value for 59 stars considered to be cluster members is  $44 \pm 12 \text{ km s}^{-1}$ . This seems to



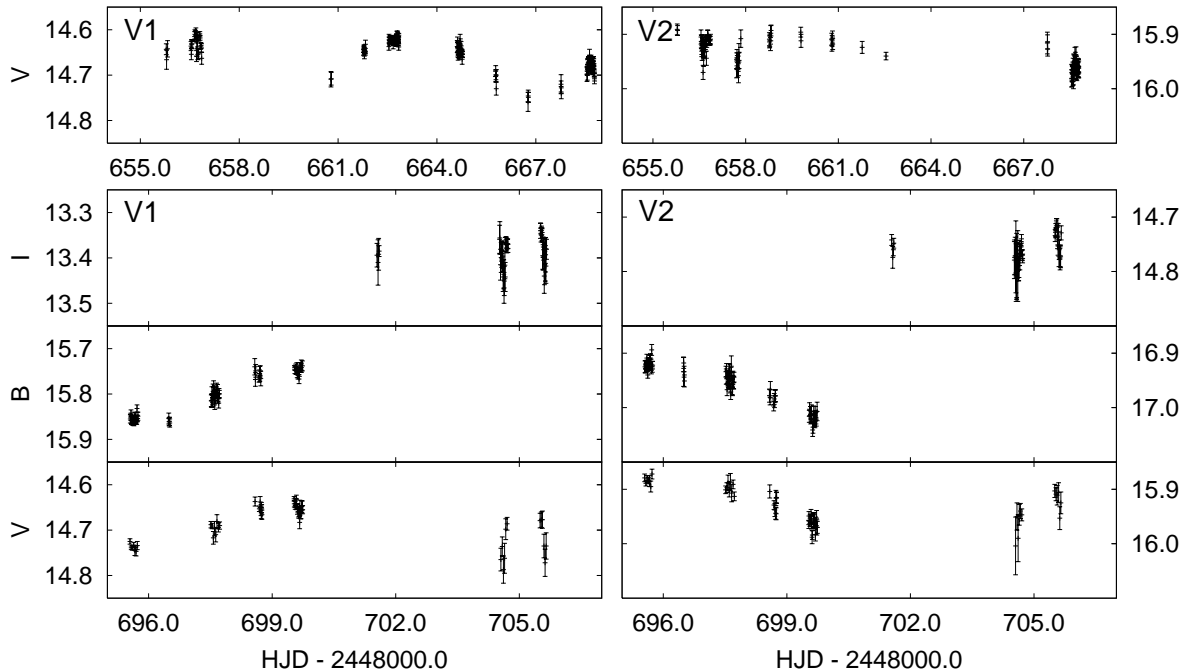


Figure 6. Unphased light curves of variables V1 and V2.

indicate that V2 has a low probability to be a radial velocity member of Melotte 66. However, this evidence is weak as the radial velocity of V2 is likely to be variable.

Some indication of membership status can be provided for 4 contact binaries. We have applied the absolute brightness calibration established by Rucinski (2000) to estimate their absolute magnitudes. The calibration gives  $M_V$  as a function of unreddened color and orbital period. We adopted reddening of  $E(V-I) = 0.22$  resulting from  $E(B-V) = 0.16$  advocated by Anthony-Twarog, Twarog & Sheeran (1994). Using dereddened  $V-I$  colors and periods listed in Table 3 we obtained  $M_V = 3.51$ ,  $M_V = 3.07$ ,  $M_V = 3.79$  and  $M_V = 6.33$  for V4, V6, V8 and V9, respectively. The apparent distance moduli of these four variables follow from the observed values of  $V_{max}$ . We obtained  $(M-m)_V = 13.14$ ,  $(M-m)_V = 14.17$ ,  $(M-m)_V = 14.36$  and  $(M-m)_V = 13.78$  for V4, V6, V8 and V9, respectively. These values can be compared with the apparent distance modulus of the cluster of  $(M-m)_V = 13.75$  as measured by Kassis et al. (1997). The formal error of  $M_V$  obtained from Rucinski's calibration is about 0.3 mag and so the estimated distance moduli are consistent with cluster membership for all four contact binaries. This conclusion holds if we adopt  $E(B-V) = 0.23$  for the cluster reddening as implied by maps of Schlegel et al. (1998).

### 3.1 Search for cataclysmic variables

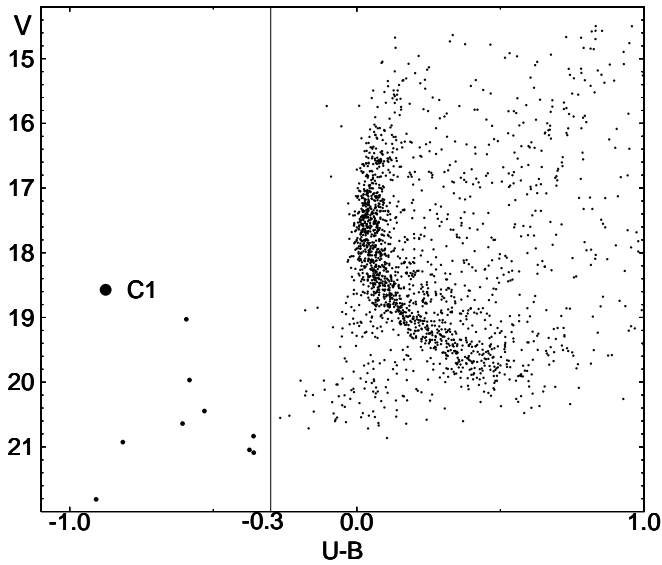
So far there are only 3 confirmed and one candidate cataclysmic variables known in the whole sample of galactic open clusters: one in M 67 (Gilliland et al. 1991), two in NGC 6791 (Kaluzny et al. 1997) and one in NGC 2158 (Mochejska et al. 2006). All of these clusters are old, and as Melotte 66 is an old and rich cluster we decided to search it for possible cataclysmic variables. Two methods were used.

First we used the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000) to look for objects showing outbursts. Cataclysmic variables of dwarf novae type have average  $M_V = 7.5$  at quiescence with outburst magnitudes spanning the range 2–8 mag (Warner 1995). At the cluster distance they would be observed at  $V \approx 21$  at minimum light and at  $13 < V < 19$  at maximum light. With a limiting magnitude of our observations of  $V \approx 21$  it should be possible to detect objects of this type while they are in outburst. Our search gave a negative result.

The second method used relies on the fact that cataclysmic variables have blue  $U-B$  colors. In Fig. 7 we show a  $V/U-B$  diagram for the cluster field. It contains 10 objects with  $U-B < -0.3$ . For 7 of these objects we have time series photometry obtained with the FORD2 camera and for 2 photometry obtained with TEK2 camera. Examination of these light curves showed that none of the objects shows any convincing evidence for variability. The brightest of the blue objects, which we denote C1, has  $V = 18.57$ ,  $B-V = 0.07$  and  $U-B = -0.87$ . The lack of evidence for variability, including comparison of photometry from 1992 and 1999 seasons, indicates that it is unlikely to be a quasar. It is possible that the star is a hot subdwarf belonging to the cluster. We note that C1 is located very close to the projected cluster centre. Very few confirmed hot subdwarfs are known in open clusters and it is of interest to obtain a spectrum of C1 to clarify its nature. If C1 is a member of the cluster then its absolute magnitude is  $M_V = 5.4$ . This value corresponds to the faint end of the absolute magnitude distribution observed for hot subdwarfs in the field and in globular clusters (Lisker et al. 2005; Moehler et al. 2002, 2004).

**Table 3.** Parameters of variables from the field of Melotte 66

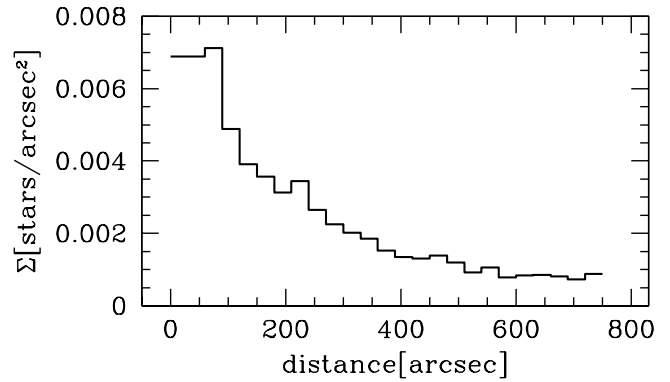
ID	$V_{max}$	$(V - I)_{max}$	$(B - V)_{max}$	$\Delta V$	$P$ [days]	$T_0$ HJD 2448000+	Remarks
V1	14.626	1.29	1.10	0.15:	$P \sim 8^d$	—	periodic?
V2	15.884	1.18	0.99	0.1:	—	—	—
V3	16.341	0.45	0.37	0.30	0.8015(2)	657.7128	Ecl
V4	16.65	0.79	0.61	0.17	0.4020(17)	656.6764	Ecl-EW
V5	17.03	0.85	0.65	0.15	0.7413(2)	658.7648	Ecl
V6	17.24	0.96	—	0.12	0.6974(3)	657.6511	Ecl-EW
V7	17.519	0.86	0.64	1.78	0.5942(1)	656.5508	Ecl=V345 Pup
V8	18.16	0.71	0.55	0.16	0.32903(6)	655.5672	Ecl-EW
V9	20.11	1.29	—	0.49	0.2386(4)	656.7105	Ecl-EW
V10	20.2	1.1	1.0	0.9	0.8882(9)	668.7426	Ecl

**Figure 7.**  $U - B$  versus  $V$  color-magnitude diagram of Melotte 66.

#### 4 ANALYSIS OF THE CMD

Some early photometric studies of Melotte 66 revealed an unexpectedly large widths for the cluster subgiant branch and upper main sequence (Hawarden 1976; Anthony-Twarog et al. 1979). Anthony-Twarog et al. (1994) used  $vbyH\beta$  CCD photometry to eliminate differential reddening and variations in cluster metallicity as possible causes of these large widths. They suggested a broad range of rotational velocities among cluster stars as an explanation.

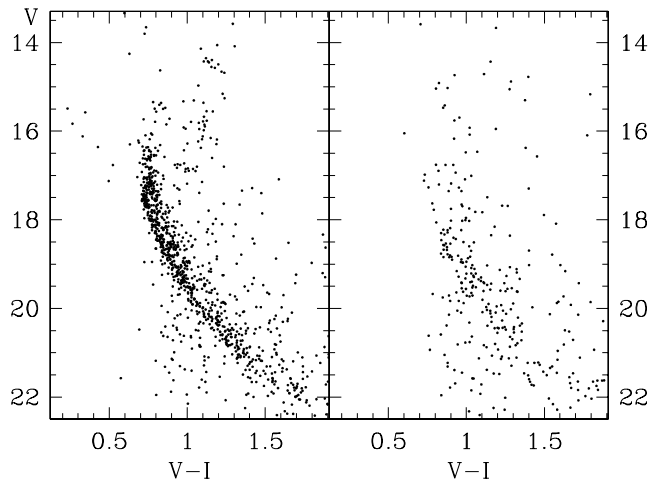
To further investigate this issue we started with a determination of the stellar density profile for the field observed with the SITE3 camera. We observed 2134 stars with  $16 < V < 21$  located near the cluster main sequence in the  $V/V - I$  CMD. The resulting density profile is shown in Fig. 8. The projected density distribution flattens at a radius of about 550 arcsec. The surface density of the field stars can be estimated at  $8.24 \pm 0.11 E - 4$  stars per  $\text{arcsec}^2$ . This implies that the SITE3 camera observations fail to cover the whole cluster E-W on the sky. By integrating the density profile shown in Fig. 8 and subtracting the contribution from the field stars we conclude that the cluster contains 1122 stars with  $16 < V < 21$  or  $2.8 < M_V < 7.8$  inside a radius of  $R = 550$  arcsec. Note that this is a conservative

**Figure 8.** Star density as a function of radial distance from the center of Melotte 66.

lower limit because no corrections for the incompleteness of the photometry have been applied. At a radius of 225 arcsec from the cluster centre the cluster surface density is still a factor of 3 higher than the field star density. In Fig. 9 we show  $V/V - I$  CMDs for two groups of stars: those lying inside a radius of  $R = 225$  arcsec from the cluster centre and those lying in the outer part of the observed field at  $R > 550$  arcsec. The inner circle and the outer region cover equal areas on the sky. For each star from the outer field a nearest match in the CMD for the inner ring was located. Subsequently a pair of stars with the lowest separation was removed from both corresponding lists. This procedure was continued until it was impossible to locate pairs with a separation  $\delta V < 0.25$  and  $\delta(V - I) < 0.15$ .

The resulting "cleaned" CMD for the inner region of Melotte 66 is shown in Fig. 10. One may notice 7 candidate blue stragglers as well as a clump of yellow stragglers at  $V \approx 15.4$  and  $V - I \approx 0.8$ . The occurrence of such objects in the cluster was first noted by Hawarden (1976) and subsequently discussed by other investigators whose papers are quoted above. Fig. 10 shows that the cluster main sequence is very sharply defined on the blue side. In particular, for  $17.4 < V < 19.5$  it is possible to distinguish a narrow, well defined main sequence corresponding to a sample dominated by single stars. Above this sequence is a second sequence consistent with a sample of binary stars with mass ratios close to unity. It merges with the "single" sequence near the turn-off region. As can be seen in Fig. 3, the eclipsing binaries V4, V5, V7 and V9 are located on the binary sequence.

The presence of a well populated binary sequence in the

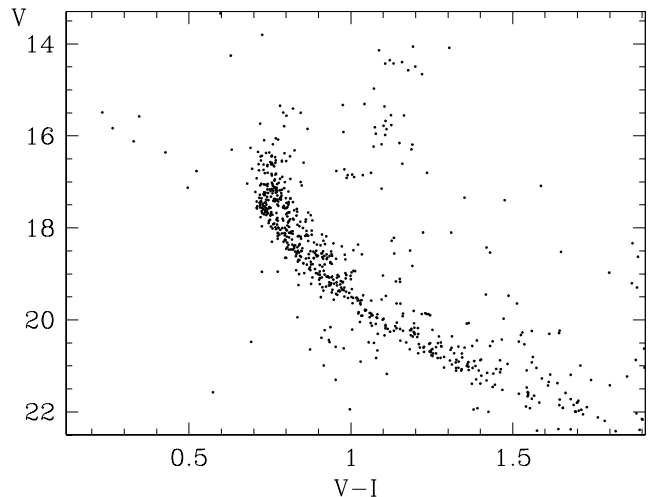


**Figure 9.** The CMD's for the field covering central part of Melotte 66 (left) and for the "outer" field (right).

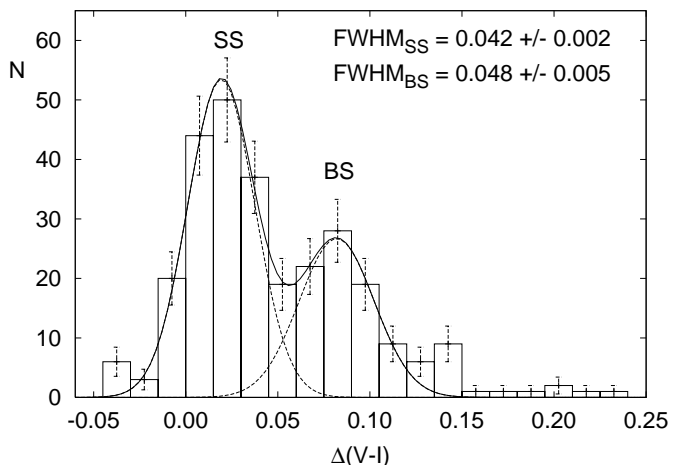
CMD of Melotte 66 has already been noticed by Kassis et al. (1997).

We have estimated the widths of these "single" and "binary" sequences using stars from the cleaned CMD in a rectangle given by  $17.5 < V < 19.5$  and  $0.7 < V - I < 1.1$ . The blue edge of the main sequence in this rectangle was fitted by second order polynomial. For each star we have calculated its distance (in color) from this polynomial. In Fig. 11 we show a histogram of star counts in bins of 0.015 in  $V - I$ . Fig. 11 shows two peaks representing the two sequences. A double-Gaussian fit to the two peaks indicates widths of  $V - I = 0.042 \pm 0.002$  and  $0.048 \pm 0.005$  for the "single" and "binary" sequences, respectively. The two sequences are well resolved in over the range  $17.5 < V < 19.5$ . At fainter magnitudes the sequences are smeared by the uncertainties of the color measurements. At  $16.0 < V < 17.5$  the sequences cross each other leading to an apparent broadening of the upper main sequence. Fig. 10 shows that the cluster subgiant branch is well populated, with 4 or 5 stars scattered on the blue side. We speculate that these stars represent an extension of the binary sequence in the turn-off region.

We have checked how the  $E(B - V)$  extinction varies across the field of the cluster based on the Schlegel et al. (1998) reddening maps. In Fig. 12. we show an  $E(B - V)$  differential reddening map with 5 arcmin resolution in a  $25 \times 25$  arcmin box centred on the cluster. It is clear that even inside the cluster radius  $\Delta E(B - V)$  can be as large as 0.09. According to Kassis et al. (1997) Melotte 66 is located about 1.1 kpc below the Galactic disk and 4.4 kpc from the Sun. The line of sight to the cluster does not cross any outer spiral arm of the Milky Way and so the observed gradients of  $E(B - V)$  occur in the interstellar matter located between the Sun and the cluster.<sup>2</sup> Our data indicate the large width of the cluster main-sequence can be explained by a high rel-



**Figure 10.** Field-star corrected CMD for the central part of Melotte 66.



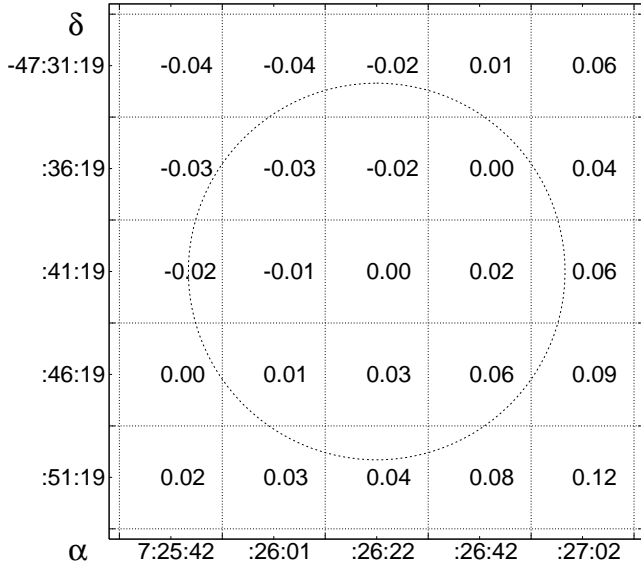
**Figure 11.** Distribution of  $\Delta(V - I)$  distances from the blue edge of the cluster main sequence (details in the text). SS and BS denote a "single" and "binary" stars sequence respectively. Solid curve is a fit to a double-gaussian. Broken curves correspond to distinct two gaussians plotted with parameters derived in the double-gaussian fit.

ative frequency of binaries among the cluster stars together with differential reddening across the cluster field.

## 5 CONCLUSIONS

We have detected a total of 10 photometric variables in the field of the old open cluster Melotte 66. Four out of eight eclipsing binaries are contact systems which are probable members of the cluster. Like other old open clusters Melotte 66 seems to have a rather high relative frequency of contact binaries. Our estimate of the total number of cluster members with  $16 < V < 21$  at 1122 stars leads to a relative frequency of EW stars of  $0.36 \pm 0.18\%$ . Note, however, that the sensitivity of our survey for variables is rather low for  $V > 20$ . This relative frequency can be compared to that observed for field stars in the solar vicinity which is estimated

<sup>2</sup> A possible extension of the Perseus spiral arm (Caswell & Haynes 1987) is present at the Galactic longitude of the cluster at a distance of about 5 kpc. However, it is unlikely that this contributes to the reddening in the direction of Melotte 66 due to the large  $z$  of the cluster.



**Figure 12.** Differential  $E(B - V)$  reddening map with 5 arcmin resolution in  $25 \times 25$  arcmin box centred at the Melotte 66 coordinates. Circle denotes cluster size  $R = 550$  arcsec.

at 0.2% for  $3.5 < M_V < 5.5$  and at 0.1% for  $M_V = 6.0$  (Rucinski 2006). Three other binaries, including a candidate blue straggler, are detached systems and one is probably a semi-detached binary. We also identified a promising candidate for a hot subdwarf cluster member.

The projected stellar density profile was obtained for the cluster field. We show that the angular radius of Melotte 66 reaches at least 550 arcsec. When corrected for the contamination by field stars the cluster CMD shows a well defined and narrow main sequence accompanied by a rich sequence of binary stars.

## ACKNOWLEDGMENTS

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